

Anomalous Higgs Couplings at the LHeC

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Abstract

The discovery of Higgs boson plays a crucial role in understanding the electroweak symmetry breaking sector. From now on, solving the dynamics of this sector needs precision measurements of the couplings of the Higgs boson to the standard model particles. In this work, we investigate the constraints on the anomalous dimension-six operators in the effective Lagrangian couplings, HWW and $HWW\gamma$, through $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ processes in a high energy envisaged ep collider which is called Large Hadron electron Collider (LHeC). We obtained the best limits on couplings of anomalous HWW and $HWW\gamma$ vertex that f_{WW} about (-0.13, 0.065) in $e\gamma \rightarrow WH\nu H$ process and f_φ about in one of the two intervals (-0.2, 0.2) or (0.65,1) in $ep \rightarrow \nu H + X$ at % 95 C.L. with the design luminosity of 10 fb^{-1} and electron beam energy of 140 GeV.

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I. INTRODUCTION

After the discovery of a new boson being compatible with Standard Model(SM) Higgs boson production and decay by ATLAS [1] and CMS [2] Collaborations at the Large Hadron Collider (LHC), the Electroweak Symmetry Breaking (EWSB) mechanism was verified experimentally leading to open up a gateway for new research field in particle physics. Now, the constraints on couplings of Higgs boson with the SM particles need to be reconsidered due to the fact that the precision measurements of its couplings will give us detailed information on EWSB of the SM and beyond. Therefore, we focus on anomalous couplings of HWW and $HWW\gamma$ vertex in ep collision where some advantages over the LHC for precision measurements such as: the ability to separate backward scattering and forward scattering due to characteristic ep kinematics and an anomalous HWW vertex will be free from possible contaminations of other Higgs boson-electroweak vector boson couplings.

Recently, there has been a new ep collider project, the Large Hadron Electron Collider (LHeC) [3], in which a newly built electron beam of 60 GeV, to possibly 140 GeV, energy collides with the intense hadron beams of the LHC (7 TeV) and with the design luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The physics programme is purposed to a search of the energy frontier, complementing the LHC and its discovery potential for physics beyond the Standard Model.

There have been several studies for anomalous couplings of HWW vertex in the literature which focus on future linear e^+e^- collider [4–10] and its $e\gamma$ [11, 12] and $\gamma\gamma$ [13–16] modes, hadron colliders [17–25] and also ep collider [26]. In Ref. [26], the constraints on anomalous CP-conserving and CP-violating couplings of HWW vertex coming from dimension-five operators in the effective Lagrangian are studied. Furthermore, we will analyze the anomalous couplings of HWW and $HWW\gamma$ vertex coming from dimension-six operators in the effective Lagrangian.

The Higgs-vector boson vertices are uniquely assigned in the SM. In some models deviations from these vertices appears, such as non-pointlike character of boson and through interactions beyond the SM. We do not have a specific model to analyze for the effect of non-SM couplings. We investigated anomalous Higgs-vector boson couplings in a model independent way by means of effective non-renormalizable Lagrangian approach which keep

the SM gauge group [5, 27]

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{k=1}^{\infty} \frac{1}{(\Lambda^2)^k} \sum_i f_i^{(k)} Q_i^{d_k} \quad , \quad (1)$$

where $d_k = 2k + 4$ denotes the dimension of operators and Λ is the energy scale of new interactions. We study only to complete set of the dimension-6 operators.

In this framework, there are only two relevant operators that Higgs boson couplings to electroweak vector bosons:

$$\frac{1}{\Lambda^2} \left\{ \frac{1}{2} f_{\varphi} \partial_{\mu} (\Phi^+ \Phi) \partial^{\mu} (\Phi^+ \Phi) + f_{WW} \Phi^+ (\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}) \Phi \right\}. \quad (2)$$

We use the formalism of [28] in writing for HWW and $HWW\gamma$ vertices in unitary gauge which follow from the effective Lagrangian (1) and (2):

$$\Gamma_{\mu\nu}^{HWW}(p, q, r) = \frac{eM_W}{s_W} \left\{ \left(1 - \frac{1}{4} f_{\varphi} \frac{v^2}{\Lambda^2}\right) g_{\mu\nu} + f_{WW} \frac{1}{\Lambda^2} [g_{\mu\nu} (q \cdot r) - q_{\nu} r_{\mu}] \right\} \quad (3)$$

and

$$\Gamma_{\mu\nu\alpha}^{HWW\gamma}(p, q, r, l) = \frac{e^2 M_W}{s_W} 2f_{WW} \frac{1}{\Lambda^2} \left\{ g_{\mu\nu} (q - r)_{\alpha} - q_{\nu} g_{\mu\alpha} + r_{\mu} g_{\nu\alpha} \right\} \quad (4)$$

where $v = \frac{2M_W}{e} s_W$ is the vacuum expectation value; p, q, r and l are the momenta of the H, W^+, W^- and γ fields, respectively. μ, ν and α denotes the W 's and γ fields, respectively. If the values of f_{WW} and f_{φ} are zero in $\Gamma_{\mu\nu}^{HWW}$ vertex, it corresponds to the SM vertex at tree level. The second vertex $\Gamma_{\mu\nu\alpha}^{HWW\gamma}$ does not occur in the SM at tree level. All calculations were performed by means of computer package the CalcHEP [29], after implementation of the vertices (3) and (4) with taking $\Lambda = M_W$ and $m_H = 125$ GeV.

II. THE CROSS SECTIONS OF $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ AND $e\gamma \rightarrow WH\nu$ PROCESSES

The production mechanism for a Higgs boson in the WW fusion at the LHeC is $ep \rightarrow \nu H + X$ as shown in Fig. 1. This process has a single Feynman diagram involving the HWW vertex. In Fig. 2, we display the total cross sections depending on incoming electron energy for the reaction $ep \rightarrow \nu H + X$ including only anomalous HWW coupling with taking

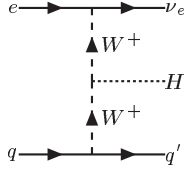


FIG. 1: Tree-level Feynman diagram for the process $ep \rightarrow \nu H + X$.

$f_{WW}(f_\varphi)=1$ (0), $f_\varphi(f_{WW})=1$ (0) and $f_{WW}=f_\varphi=0$ for illustration purpose by using parton distribution functions library CTEQ6L [30]. From this figure we can see that, the only contribution from the SM part of the Eq. (3) in the case of $f_{WW}=f_\varphi=0$ (solid line), from both f_φ (f_{WW}) coupling and SM part in the case of $f_\varphi=1(0)$, $f_{WW}=0$ (1) to $ep \rightarrow \nu H + X$ process.

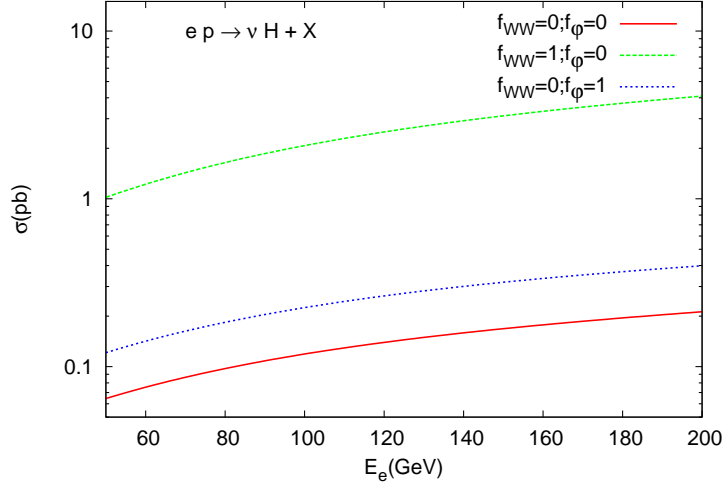


FIG. 2: The total cross sections depending on incoming electron energy for the process $ep \rightarrow \nu H + X$ including only anomalous HWW coupling in ep collisions at the LHeC with taking $m_H=125$ GeV.

Efficient γp collisions can be realized with real γ , produced using Compton back scattering of laser beam off the high energy electron beam, only on the base of linac ring type ep colliders [31]. In this framework, we consider $\gamma p \rightarrow WH + X$ reaction to see the effect of both HWW and $HWW\gamma$ couplings. The tree-level diagrams of the process $\gamma p \rightarrow WH + X$ are depicted in Fig. 3. We present in Fig. 4, the total cross section as function of incoming electron beam energy for this process by using the spectrum of photons scattered backward from

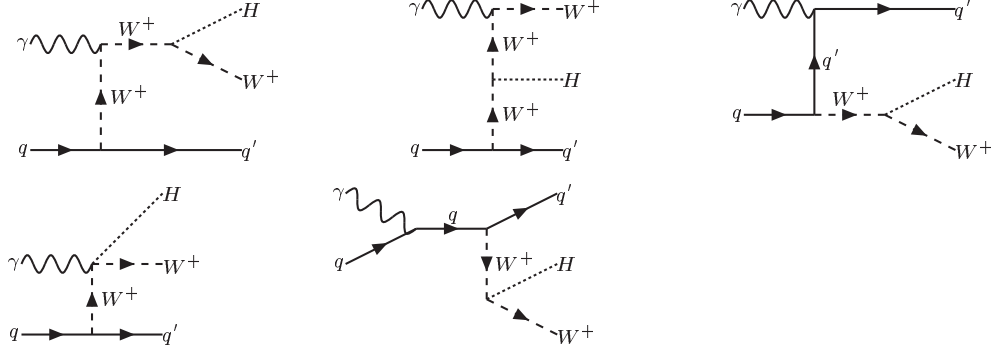


FIG. 3: Tree-level Feynman diagrams for the process $\gamma p \rightarrow WH + X$.

the interaction of laser light with the high energy electron beam [32] in case $f_{WW}=f_\varphi=0$, $f_{WW}(f_\varphi)=1(0)$ and $f_\varphi(f_{WW})=1(0)$. As we can see, contribution of the $HWW\gamma$ vertex, described in Eq. (4), leads to an increase of two orders in the cross section.

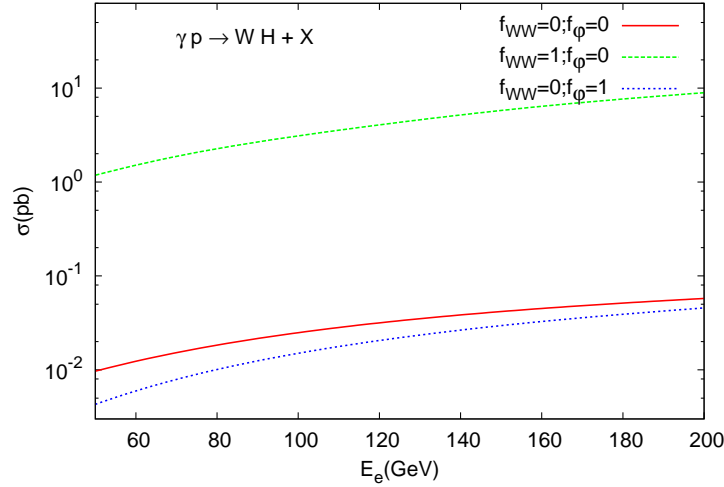


FIG. 4: The total cross sections depending on incoming electron energy for $\gamma p \rightarrow WH + X$ including anomalous HWW and $HWW\gamma$ couplings in ep collisions at the LHeC with taking $m_H=125$ GeV.

The another mode of ep colliders is $e\gamma$ option where γ is elastic photon emission coming from proton. The equivalent photon spectrum are described by the equivalent photon approximation (EPA) [33] which embedded in CalcHEP. The $e\gamma \rightarrow WH\nu$ process in ep collision is described by tree-level diagrams in Fig. 5. These diagrams contains anomalous HWW and $HWW\gamma$ couplings. In Fig. 6, we plot the total cross section depending on

incoming electron energy for $f_{WW}=f_\varphi = 0$, $f_{WW}(f_\varphi) = 1(0)$ and $f_\varphi(f_{WW})=1(0)$ by using EPA.

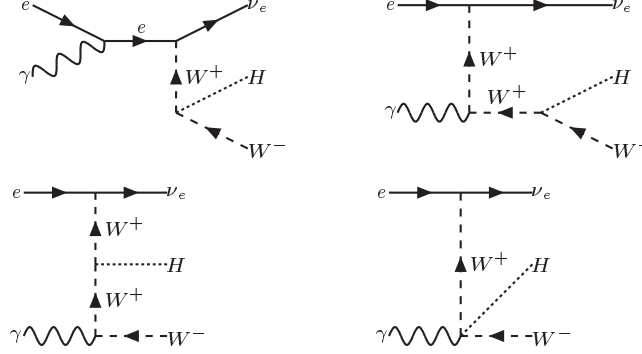


FIG. 5: Tree-level Feynman diagrams for the process $e\gamma \rightarrow WH\nu$.

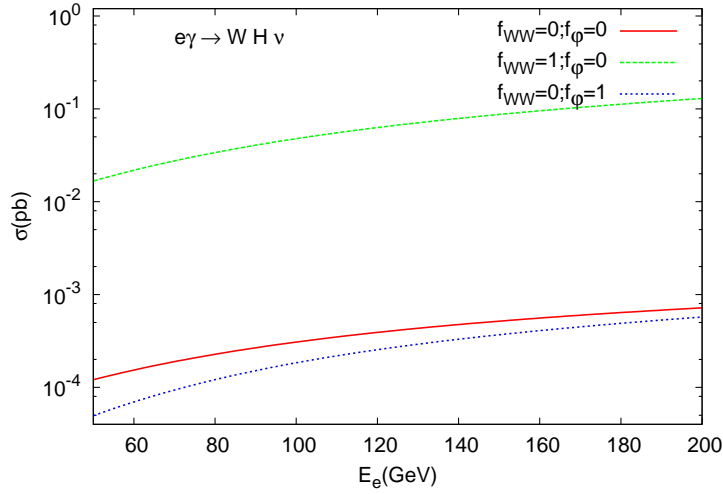


FIG. 6: The total cross sections depending on incoming electron energy for $e\gamma \rightarrow WH\nu$ including anomalous HWW and $HWW\gamma$ couplings in ep collisions at the LHeC with taking $m_H=125$ GeV.

The calculated total cross sections of the $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ processes with taking 140 GeV of energy of incoming electron as function of the anomalous couplings f_{WW} (f_φ) are shown in the left panel (right panel) of Fig. 7. Here, we see that $ep \rightarrow \nu H + X$ process is more sensitive to f_φ as compared to other processes, while $\gamma p \rightarrow WH + X$ process is strongly dependent upon the f_{WW} .

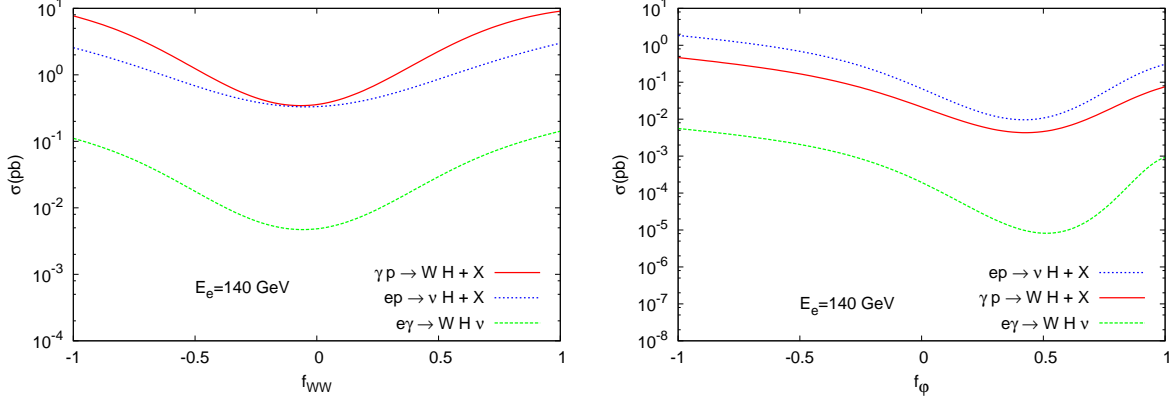


FIG. 7: The total cross sections of $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ processes as functions of f_{WW} (left panel) and f_ϕ (right panel) with taking $E_e=140$ GeV and $m_H=125$ GeV.

III. LIMITS ON THE ANOMALOUS HIGGS COUPLINGS

One-parameter χ^2 test was applied without a systematic error to obtain 95% confidence level (C.L.) on the upper limits of the f_ϕ and f_{WW} . The χ^2 function is

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma(f_\phi, f_{WW})}{\sigma_{SM} \delta} \right)^2 \quad (5)$$

where $\delta = \frac{1}{\sqrt{N}}$ is the statistical error. The number of events are given by $N = \sigma_{SM} L_{int}$ where L_{int} is the integrated luminosity. When calculating number of events we assume all W bosons decay leptonically in the final state, the dominant Higgs boson decay to $b\bar{b}$, the efficiency for b-tagging to be $\epsilon = 60\%$ and the fake rejection factors of 0.01 for light quarks. And also we applied cuts for missing transverse energy (MET) for neutrinos to be $MET > 25$ GeV, transverse momentum of quarks to be $p_T^{b,j} > 10$ GeV and pseudorapidity of quarks to be $|\eta|^{b,j} < 2.5$. With assuming these restrictions, we have calculated $\sigma_{SM} = 0.186$ pb for $ep \rightarrow \nu b\bar{b}j + X$, $\sigma_{SM} = 5.98 \times 10^{-2}$ pb for $\gamma p \rightarrow \nu b\bar{b}Wj + X$ and $\sigma_{SM} = 1.87 \times 10^{-4}$ pb for $e\gamma \rightarrow \nu b\bar{b}W + X$ processes.

In Figs. 8, 9 and 10, we present the sensitivity contour plot at % 95 C.L. for the anomalous couplings, f_{WW} (left panel) and f_ϕ (right panel) as function of integrated luminosity through $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ processes with $E_e=140$ GeV. As you can seen from this figures, the best limits on the anomalous couplings f_{WW} and f_ϕ coming from $e\gamma \rightarrow WH\nu$ and $ep \rightarrow \nu H + X$. In Fig. 11, we exhibited χ^2 as a function of f_{WW} (left panel) and f_ϕ (right panel) through $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ with

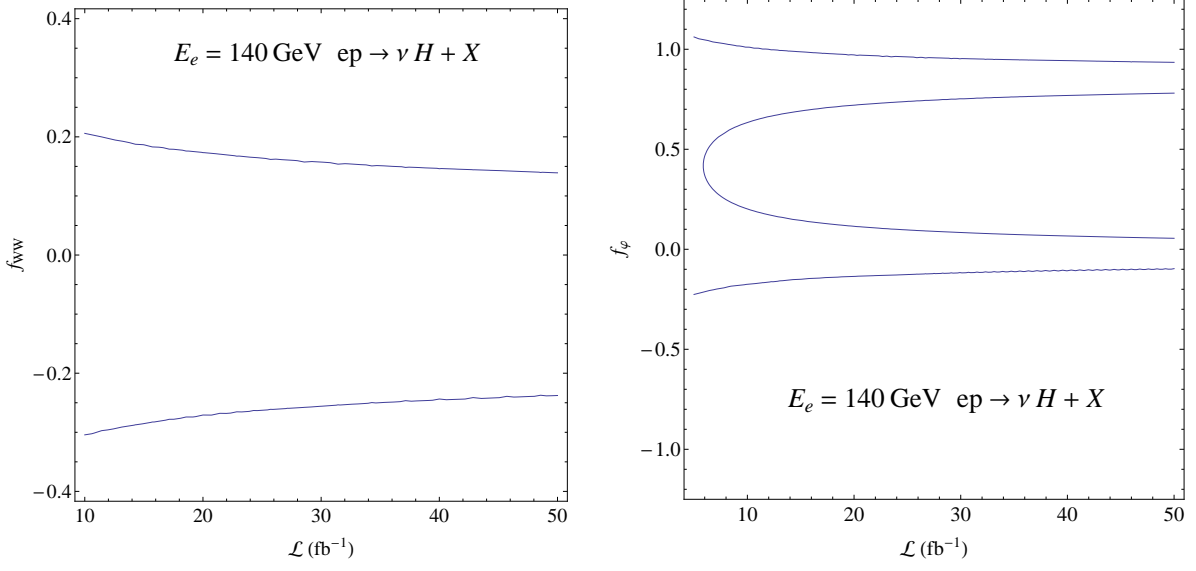


FIG. 8: The contour plot for the couplings f_{WW} (left panel) and f_φ as function of integrated luminosity with 95% C.L. for the process $ep \rightarrow \nu H + X$ with $E_e=140$ GeV.

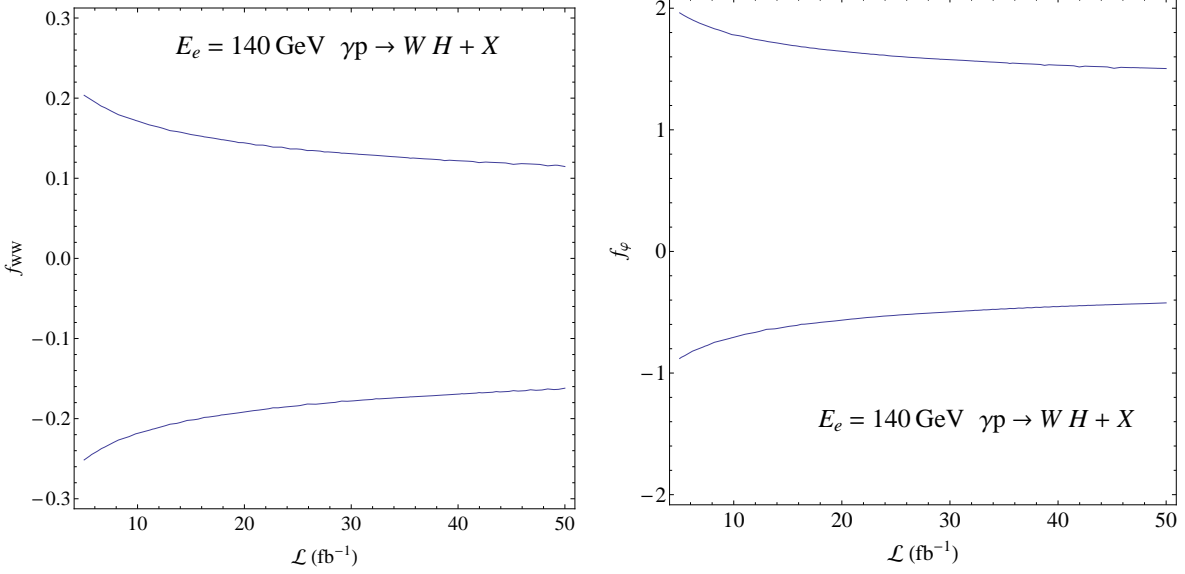


FIG. 9: The same as Fig. 8 but for $\gamma p \rightarrow WH + X$ process.

$E_e=140$ GeV and design luminosity, $L = 10 \text{ fb}^{-1}$. A distinct feature of this figure is that the limiting on anomalous couplings to see clearly at % 95 C.L.. If the LHeC has collected 10 fb^{-1} of data, the bounds on f_{WW} would be $(-0.13, 0.065)$ in $e\gamma \rightarrow WH\nu$ process and f_φ would be in one of the two intervals $(-0.2, 0.2)$ or $(0.65, 1)$ in $ep \rightarrow \nu H + X$ at % 95 C.L.

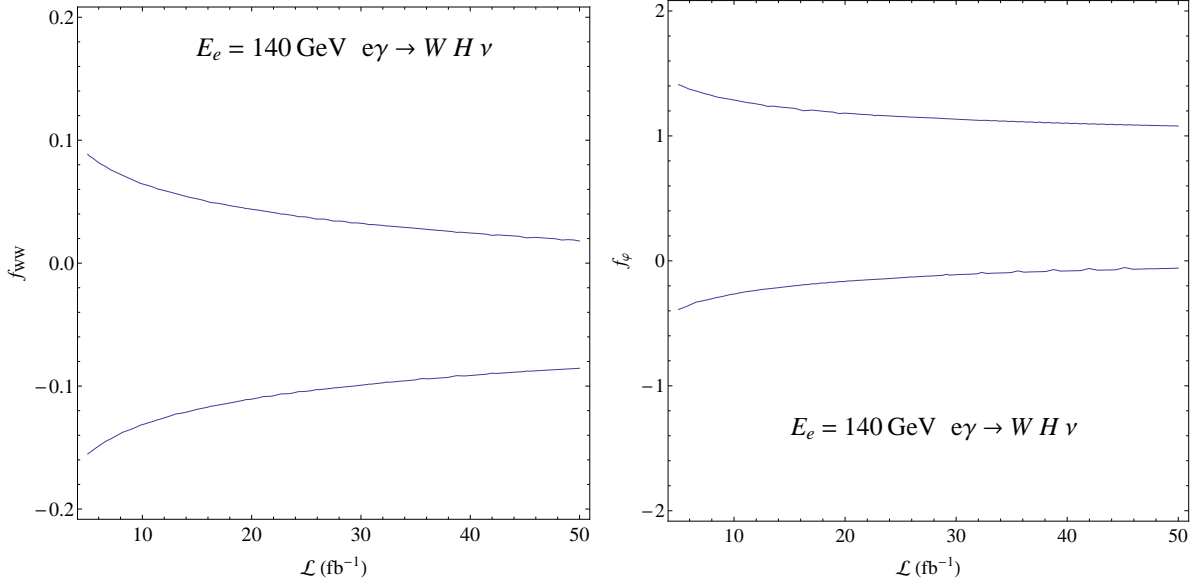


FIG. 10: The same as Fig. 8 but for $e\gamma \rightarrow WH\nu$ process.

While the indirect 95% C.L. constraints of the L3 collaboration [21, 34] for f_{WW} are in the interval of $(-0.17, 0.17)$ with taking $m_H=120$ GeV and $(-0.097, -0.012)$ or $(0.18, 0.26)$ from available data from Tevatron and LHC [25].

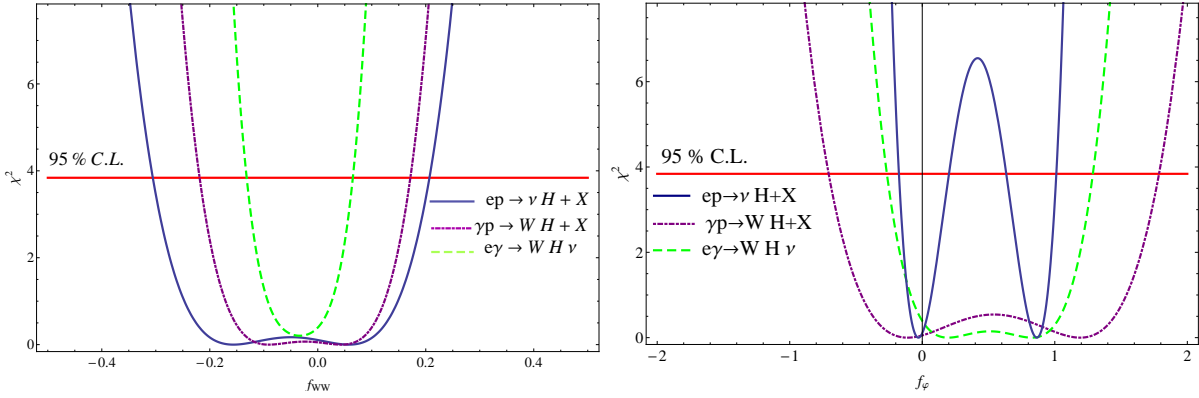


FIG. 11: χ^2 as a function of f_{WW} (left panel) and f_ϕ (right panel) through $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ with $E_e=140$ GeV and design luminosity of 10 fb^{-1} .

IV. CONCLUSION

In this work, we focused on couplings of HWW and $HWW\gamma$ vertices to constrain deviations from the SM behavior leading the effects of dimension-six effective operators. We

have examined this effect in $ep \rightarrow \nu H + X$, $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ processes at the LHeC to compare which is the best limits on the anomalous couplings. We obtained the best limits on f_{WW} about $(-0.13, 0.065)$ in $e\gamma \rightarrow WH\nu$ process and f_φ about lie in one of the two intervals $(-0.2, 0.2)$ or $(0.65, 1)$ in $ep \rightarrow \nu H + X$ at % 95 C.L. with the design luminosity value. Our results for anomalous couplings are comparable with limits from LHC and Tevatron data. Finally, the LHeC is a suitable platform to complement the LHC results for searching of anomalous HWW and $HWW\gamma$ couplings in $ep \rightarrow \nu H + X$ process as well as $\gamma p \rightarrow WH + X$ and $e\gamma \rightarrow WH\nu$ processes.

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